EARTH PRESSURES WITH SLOPING BACKFILL

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ABSTRACT: This paper presents experimental data of earth pressure acting against a vertical rigid wall, which moved away from or toward a mass of dry sand with an inclined surface. The instrumented retaining-wall facility at National Chiao Tung University (NCTU) Taiwan, was used to investigate the variation of earth pressure induced by the translational wall movement. Based on experimental data, it has been found that the earth-pressure distributions are essentially linear at each stage of wall movement. Both the wall movement required for the backfill to reach an active state and the wall movement needed for the backfill to reach a passive state increase with an increasing backfill inclination. The experimental active and passive earth-pressure coefficients for various backfill sloping angles are in good agreement with the values calculated by Coulomb's theory. It may not be appropriate to adopt the Rankine theory to determine either active or passive earth pressure against a rigid wall with sloping backfill.

INTRODUCTION

Retaining walls are frequently used to hold back the earth and maintain a difference in the elevation of the ground surface. In highway construction, they are used along cuts and fills where space is inadequate for the appropriate side slopes. Fig. 1 illustrates the retaining walls constructed on a slope. After cut and fill, a flat area is created for road construction or housing. On the uphill side of the upper retaining wall, active earth pressure developed with a positive backfill inclination ($+i$ angle). On the downhill side of the lower wall, passive earth pressure developed with a negative backfill inclination ($-i$ angle). For a safe design of the retaining structure previously mentioned, it is necessary to determine the magnitude and distribution of the active and passive stresses acting on the walls.

Traditionally, civil engineers calculate the active and passive earth pressure against the wall following either Coulomb or Rankine's theory. Another popular method to estimate the earth pressure is the logarithmic-spiral method proposed by Terzaghi (1943). It should be emphasized that, depending on the backfill sloping angle, the active and passive thrusts calculated with these methods could be quite different. From an engineering point of view, it would be interesting to know which method would be more appropriate to use for design.

Valuable experimental work associated with earth pressure has been conducted by Terzaghi (1932), Schofield (1961), Rowe and Peaker (1965), Mackey and Kirk (1967), Narain et al. (1969), James and Bransby (1970), Matteotti (1970), Bros (1972), Sherif and Mackey (1977), Sherif et al. (1982), Sherif et al. (1984), Duncan and Seed (1986), Fang and Ishibashi (1986), Duncan et al. (1991), Fang et al. (1994), and other researchers. Unfortunately, most of the work is associated with a backfill with horizontal surface. In fact, little experimental justification has been reported in the literature regarding the development of active and passive earth pressures against a wall with sloping backfill. As a result, how to evaluate the validity of the theoretical solutions remained problematic.

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This paper presents experimental data of earth pressure against a vertical rigid wall, which moved away from or toward a mass of dry sand with a stress-free inclined surface. The backfill sloping angles used for the tests ranged from $-20°$ to $+20°$ as shown in Fig. 2. All of the earth-pressure experiments mentioned in this paper were conducted in the National Chiao Tung University (NCTU) retaining-wall facility, which is described in the following section. Horizontal earth pressure against the wall is measured with the soil-pressure transducers mounted on the model wall. Due to the scale effect, it may not be appropriate to predict the behavior of larger walls from the results obtained from small-scale models. However, the test findings should enhance a better understanding regarding the effect of backfill inclination on the development of earth pressure.

NATIONAL CHIAO TUNG UNIVERSITY RETAINING-WALL FACILITY

The entire facility consists of four components, namely, the model retaining wall, soil bin, driving system, and data-acquisition system.

The movable model retaining wall and its driving system are illustrated in Fig. 3. The model wall is a 1,000 mm wide, 550 mm high, and 120 mm thick solid plate, and is made of steel. For the test shown in Fig. 3, the effective wall height H (or height of backfill at the soil-wall interface above the wall base) is only 300 mm. The retaining wall is vertically supported by two unidirectional rollers and is laterally supported by four driving rods. The 1,000 mm wide, 337 mm high, and 120 mm thick steel plate on top of the movable wall is designed to resist the uplift components of passive earth pressure. To investigate the distribution of earth pressure, soil-pressure transducers (SPT) are attached to the model retaining wall as shown in Fig. 4. Ten strain-gauge-type earth-pressure transducers have been arranged within the central zone of the wall. Another three transducers (SPT 10, 11, and 12) have been mounted between the central zone and sidewall to investigate

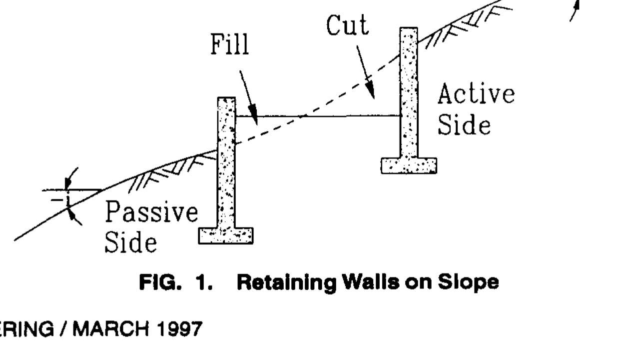

FIG. 1. Retaining Walls on Slope

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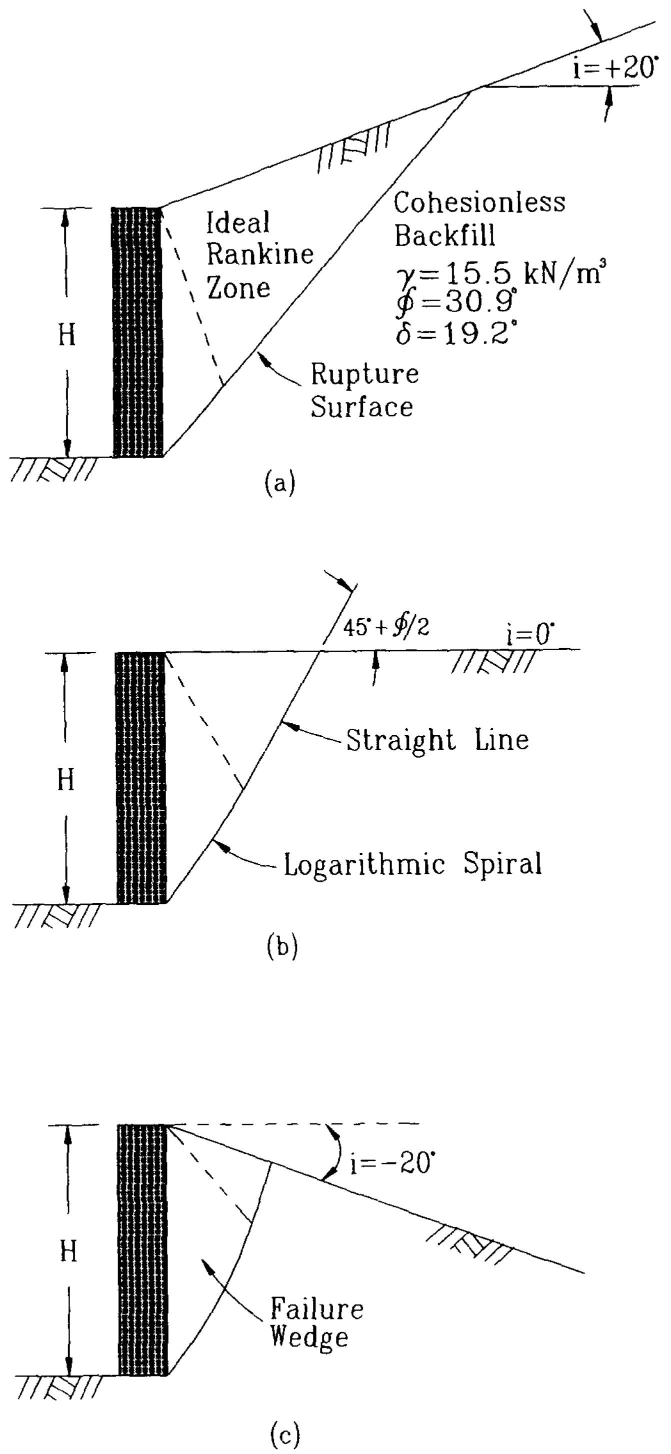

FIG. 2. Active Wedge Calculated with Terzaghi's Log-Spiral Method

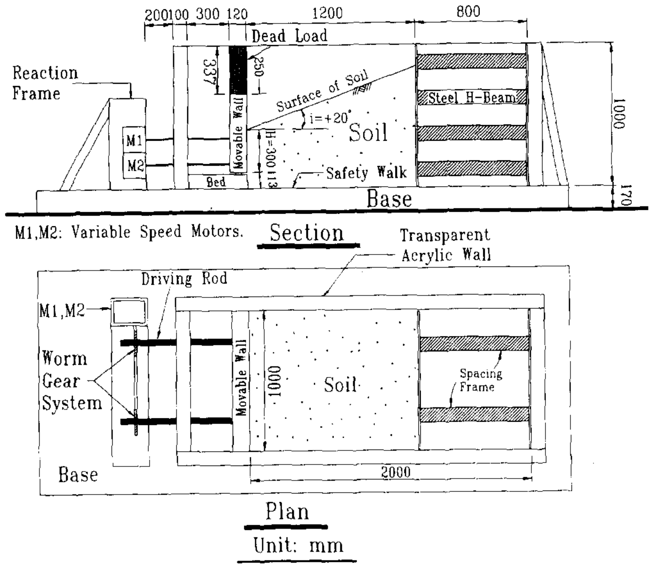

FIG. 3. National Chiao Tung University Retaining-Wall Facility

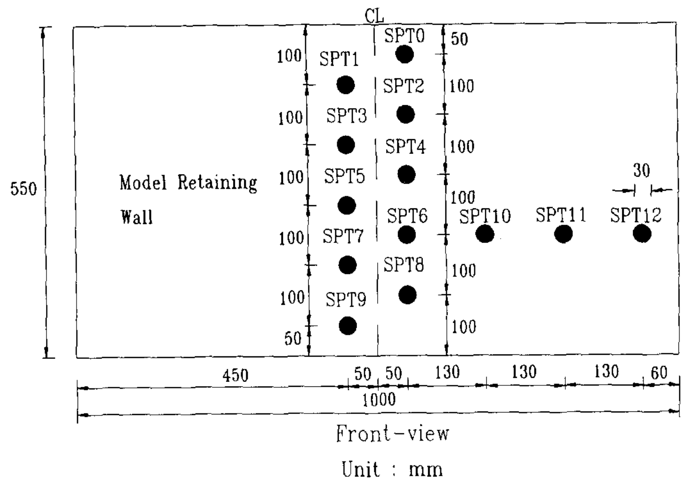

FIG. 4. Locations of Soil-Pressure Transducers

the sidewall effect. To eliminate the soil-arching effect, all earth-pressure transducers are quite stiff and are installed flush with the face of the wall. For passive tests Kyowa BE-2KRS17 (196 kN/m^2 capacity) transducers are used. For active experiments, since the overburden pressure is very small, extremely sensitive Kyowa PGM-02KG (19.6 kN/m^2 capacity) transducers are used.

The soil bin is fabricated of steel members with inside dimensions of 2,000 × 1,000 × 1,000 mm (see Fig. 3). Both sidewalls of the soil bin are made of 30 mm thick transparent acrylic plates through which the behavior of backfill can be observed. The bottom of the soil bin is covered with a layer of SAFETY WALK manufactured by 3M Company to provide adequate friction between the soil and the base of the bin. According to the general wedge theory (Terzaghi 1941), the passive failure surface developed in the backfill would extend below the base of the wall. As shown in Fig. 3, the fixed bed located below the wall serves to hold the bottom 113 mm of soil to accommodate the entire log-spiral failure surface. For active experiments it may not be necessary to fill the entire 2 m long soil bin to develop the failure wedge. To save the time and energy for soil placement, a spacing frame made of steel was put into the soil bin. However, the frame was removed for all passive experiments.

As illustrated in Fig. 3, the variable speed motors M1 and M2 (Electro, M4621AB) are used to compel the upper and lower driving rods, respectively. The shaft rotation compels the worm-gear linear actuators, and the actuator pushes or pulls the model wall. Since only the variation of earth pressure caused by the translational wall movement is investigated, therefore the motor speeds at M1 and M2 were kept the same for all experiments in this study.

Due to the considerable amount of data collected by SPTs, a data-acquisition system is used. The analog signals from the sensors are digitized by an analog-to-digital converter. The digital data are then stored and processed by a microcomputer. For more details regarding the NCTU retaining-wall facility, the reader is referred to Wu (1992) and Fang et al. (1994).

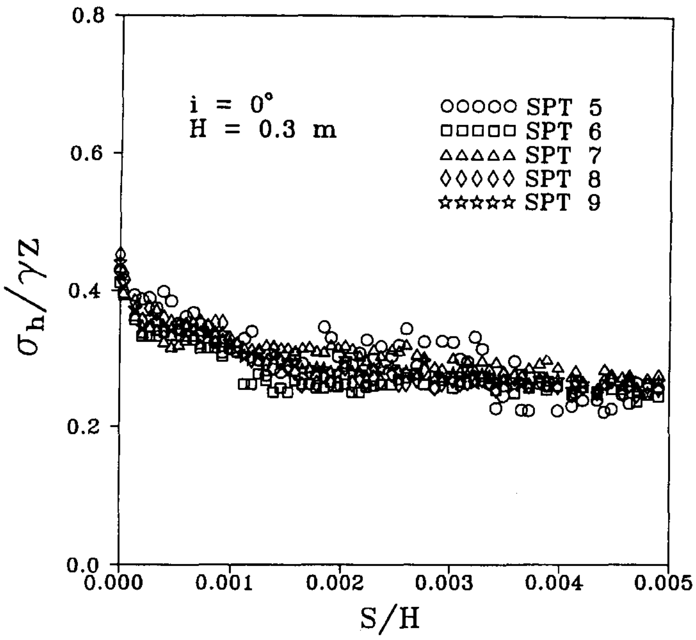

FIG. 5. Relationship between $\sigma_h/\gamma z$ and S/H

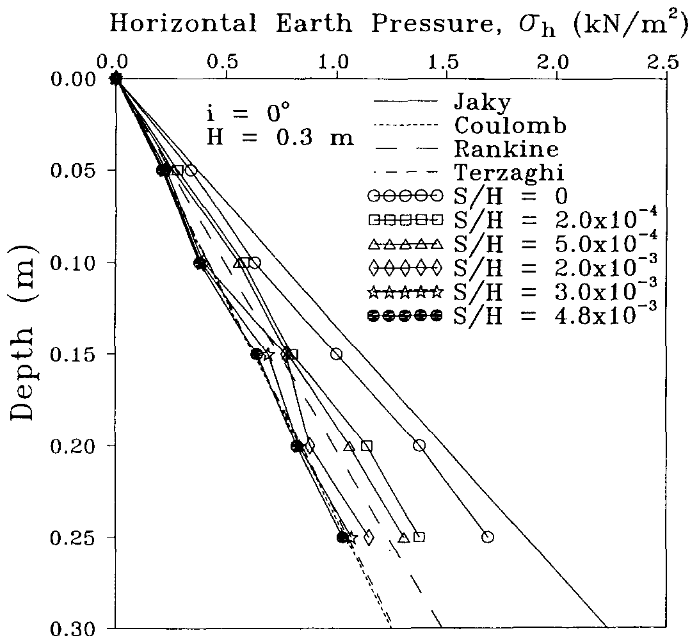

FIG. 6. Distributions of Lateral Earth Pressure for Horizontal Backfill

BACKFILL AND INTERFACE CHARACTERISTICS

Air-dry Ottawa sand (ASTM C-109) was used throughout this investigation. Physical properties of the soil include G_s = 2.65, e_{max} = 0.76, e_{min} = 0.50, D_{60} = 0.36 mm, and D_{10} = 0.23 mm. For this study, the backfill was deposited by air pluviation from the slit of a hopper into the soil bin. The drop distance was kept to be approximately 600 mm to the soil surface through the placement process. The soil unit weight γ achieved with the pluviation method was 15.5 kN/m^3. The corresponding internal friction angle ϕ determined from direct shear tests with normal stresses less than 40 kPa was found to be 30.9°. To limit the scope of this study, only one density was used throughout all experiments.

To reduce the friction between sidewall and backfill, a lubrication layer was furnished for the earth-pressure experiments. The layer consists of a 0.2 mm thick latex rubber membrane and a thin layer of silicone grease (Shin-Etsu KS-63G). The frictional resistance developed between the sidewall and Ottawa sand was evaluated by a special direct shear test. In the test, an acrylic plate (same material as the sidewall) was placed under the upper shear box. Following the testing method suggested by Tatsuoka and Haibara (1985), it is found that, if the normal stress is greater than 40 kN/m^2, the friction angle can be successfully reduced to less than 1°. However, if the normal stress at the interface is less than 10 kN/m^2, the friction angle becomes higher. Based on the results of model wall experiments, Terzaghi (1932) found that, even without the lubrication layers, the intensity of earth pressure is practically independent of the length of the wall (inside width of the soil bin), if the length of the wall exceeds twice the wall height. For this study the width of the soil bin (W = 1.0 m) is kept to be at least twice the height of backfill.

By replacing the acrylic plate with a steel plate (same material as the model retaining wall) and removing the lubrication

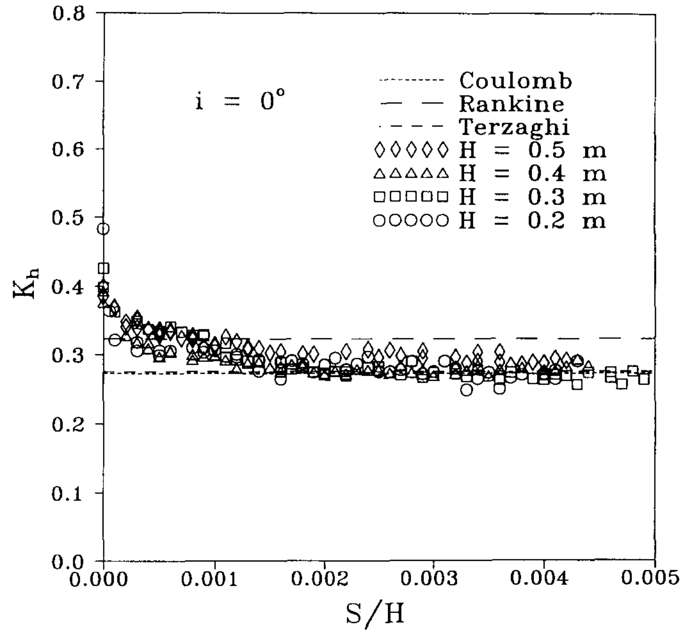

FIG. 7. Variation of K_h with Active Wall Movement for Various Backfill Heights

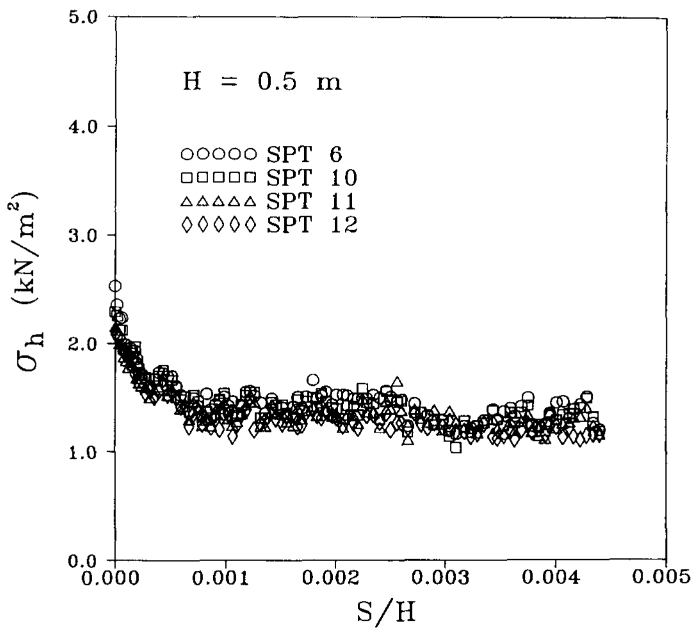

FIG. 8. Comparison of Earth Pressures Measured at Different Distances from Sidewall

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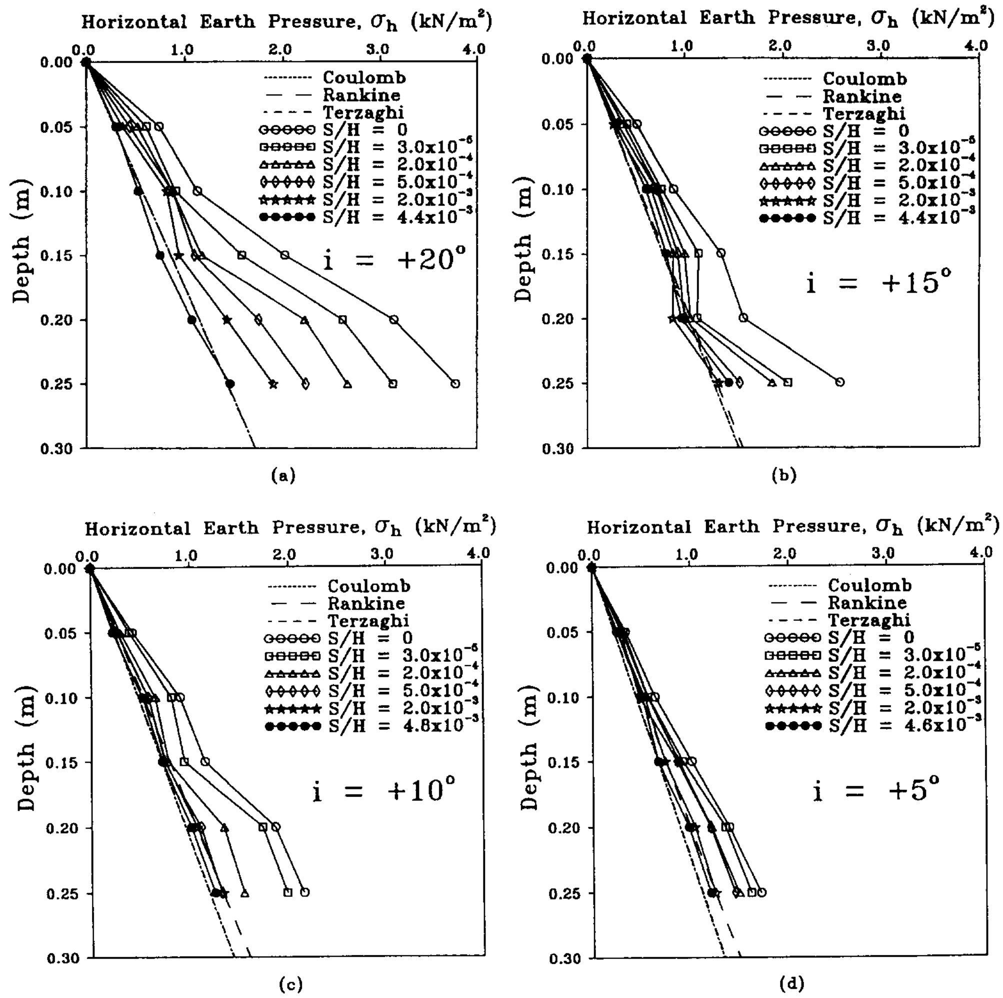

FIG. 9. Distributions of Horizontal Earth Pressure for Positive Backfill Inclinations

layer, the friction angle δ between Ottawa sand (γ = 15.5 kN/m³) and the steel plate is found to be 19.2°. The ϕ and δ angles determined from the tests are assumed for the calculation of earth pressure for Coulomb, Rankine, and Terzaghi's theories in the following sections. Figs. 2(a)–2(c) show the failure wedges for i = +20°, 0°, and −20° calculated with Terzaghi's log-spiral method. The figures will be used to interpret the experimental results in the present study.

ACTIVE TESTS RESULTS

Wall with Horizontal Backfill

At the beginning, the earth pressure behind a wall with a 0.3 m high (H = 0.3 m) and horizontal (i = 0°) backfill is investigated. After the backfill has been placed into the soil bin, the model wall slowly moves away as a solid block (translation mode) from the soil mass at a constant speed of 0.02 mm/s.

The variation of earth pressure σ_h measured at different depths as a function of horizontal wall displacement S is shown in Fig. 5. The σ_h and S have been normalized with vertical stress γz and the height of backfill H, respectively. As the wall started to move, the earth pressure decreased rapidly and eventually a limiting active pressure was reached. An active state was reached at different depths nearly simultaneously. The distribution of earth pressure at different stages of wall movement (S/H) are indicated in Fig. 6. The pressure distributions are essentially linear at each stage of deformation up to failure.

To investigate the effect of H on earth-pressure development, experiments with backfill heights of 0.2, 0.3, 0.4, and 0.5 m are conducted. In Fig. 7, the horizontal earth-pressure coefficient K_h decreases with increasing wall movement, and finally a constant total thrust is reached. It is clear that, within the range tested, the backfill height has limited influence on the development of the K_h curve. The coefficient K_h is defined as the ratio of the horizontal component of total thrust to $\gamma H^2/2$. The horizontal soil thrust is calculated by summing the pressure diagram shown in Fig. 6. The ultimate value of K_h is defined as the horizontal active earth pressure $K_{a,h}$. Due to practical difficulties, no SPT had been fixed at the bottom edge of the retaining wall. The earth pressure assumed for integration at depth H was approximated by linear extrapolation of the valid data points. However, it should be emphasized that some theoretical calculations indicate that the stress at the bottom of the wall may be much more complicated than what has been assumed.

The active condition is reached at approximately S/H = 0.0015. It should be mentioned that to locate the active point on the curve may not be an easy task. It also may be observed from Fig. 7 that both Coulomb and Terzaghi's theories would provide a good evaluation of the active thrust. However, Rankines' theory tends to overestimate the active earth pressure.

To evaluate the effect of sidewall friction, SPTs SPT6, 10, 11, and 12 are installed on the model wall at the same elevation across the wall face. Experimental data plotted in Fig. 8 indicates that, with the lubrication layer, earth pressures measured at different distances from the sidewall are in fairly good agreement. However, since the monitored stress level is very low, data fluctuation becomes apparent.

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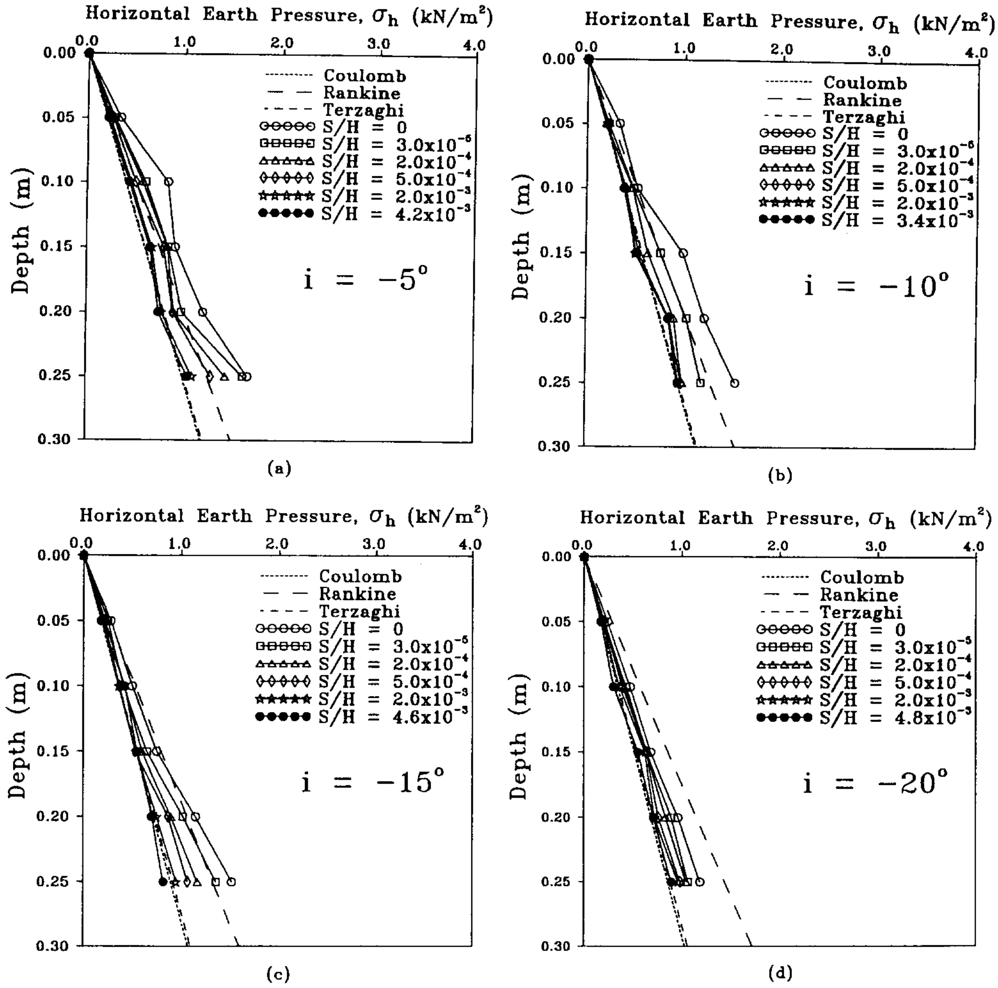

FIG. 10. Distributions of Horizontal Earth Pressure for Negative Backfill Inclinations

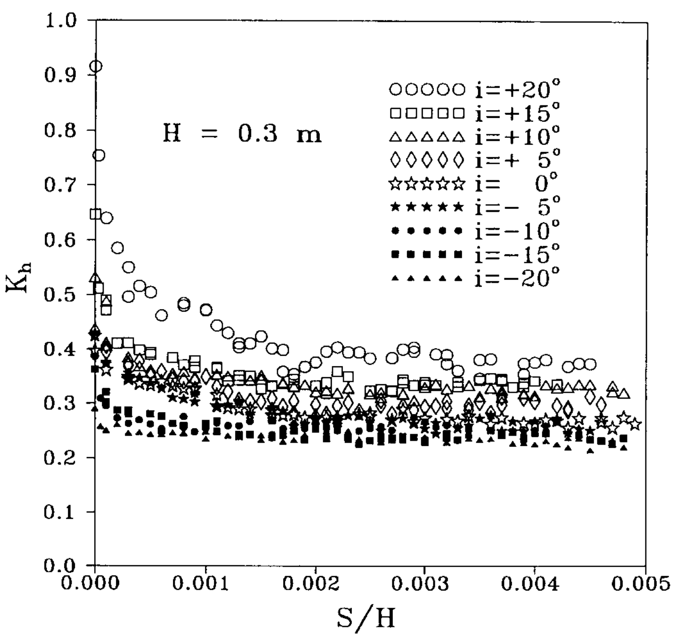

FIG. 11. Variation of K_h with Active Wall Movement for Various Backfill Inclinations

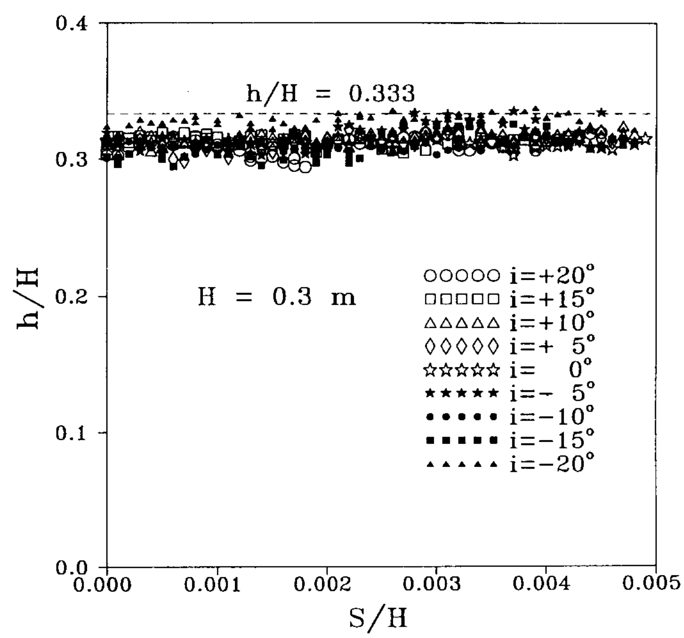

FIG. 12. Variation of *h/H* with Wall Movement for Various Backfill Inclinations

Wall with Sloping Backfill

The effects of backfill inclination on the development of active stress are discussed. Figs. 9 and 10 show the earth-pressure distributions at different stages of wall movement for positive and negative backfill inclinations, respectively. It can be seen that, for $H = 0.3$ m and i varying from $-20°$ to $+20°$, the experimental earth-pressure distributions are approximately linear at each stage of the wall movement. This implies

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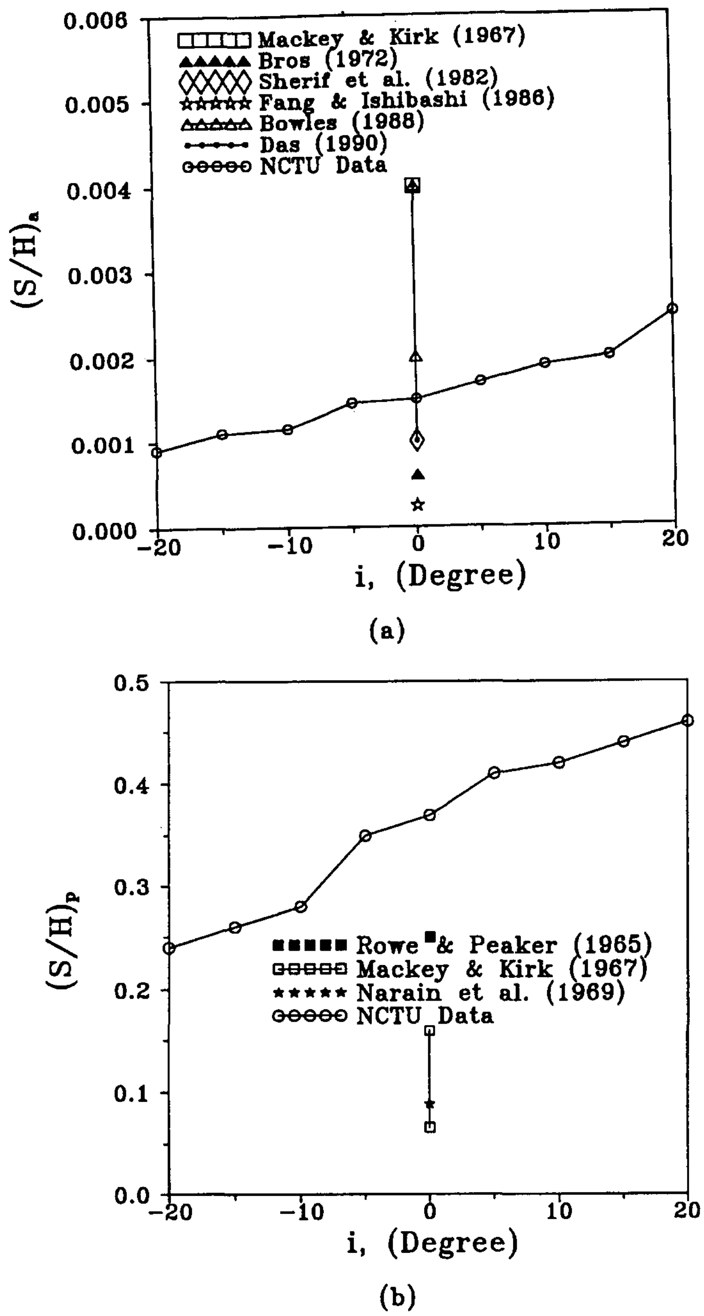

FIG. 13. $(S/H)_a$ and $(S/H)_p$ versus Backfill Inclination

that the points of application of total thrusts would act at about $H/3$ above the wall base. It is also clear in these figures that the experimental active stress distributions are in fairly good agreement with Coulomb and Terzaghi's solutions.

The variations of K_h with wall movement for various backfill inclinations are summarized in Fig. 11. It is clear from the figure that K_h decreases with increasing wall movement before reaching a stable value. It may be observed in Fig. 11 that, for the backfill with a negative sloping angle (e.g., $i = -20°$), an active state is reached at a relatively small wall movement. However, a larger wall movement is needed for a backfill with a positive sloping angle (e.g., $i = +20°$) to reach an active state. The finding is logical in view of the fact that the rupture surface illustrated in Fig. 2(c) is apparently shorter than that shown in Fig. 2(a). Fig. 12 shows that, irrespective of the backfill inclination, the points of application of the total thrusts are located at about $0.29H$ to $0.33H$ above the wall base. Note that h is defined as the distance between the point of application of total thrust and the wall base.

Fig. 13(a) shows that the wall movement required for the backfill to reach an active state $(S/H)_a$ increases with increasing backfill inclination. For the sloping angle $i = -20°$, the active wall movement required is about 0.0009. Nevertheless, for $i = +20°$ the $(S/H)_a$ needed is about 0.0025. The experimental findings reported by Mackey and Kirk (1967), Bros (1972), Sherif et al. (1982), Fang and Ishibashi (1986), Bowles (1988), and Das (1990) are also plotted in Fig. 13. It should be mentioned that the data point reported by Fang and Ishibashi (1986) was obtained for a backfill that had been densified with the sinusoidal horizontal acceleration of $0.35g$ for 10 s. It is apparent that soil density plays an important role regarding the determination of $(S/H)_a$.

Fig. 14 shows the relationship between the active earth-pressure coefficient $K_{a,h}$ and the backfill sloping angle i. It is clear from this figure that the experimental $K_{a,h}$ increases with increasing backfill inclination. The $K_{a,h}$ values calculated with

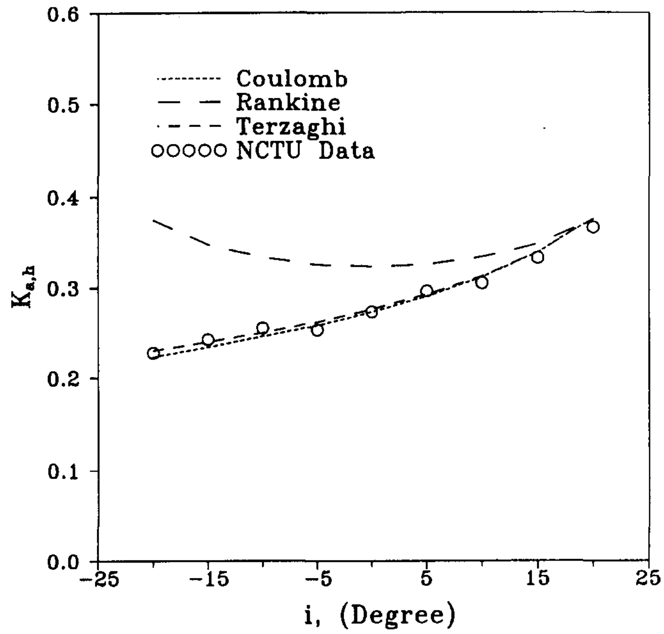

FIG. 14. Active Earth-Pressure Coefficient $K_{a,h}$ versus Backfill Inclination

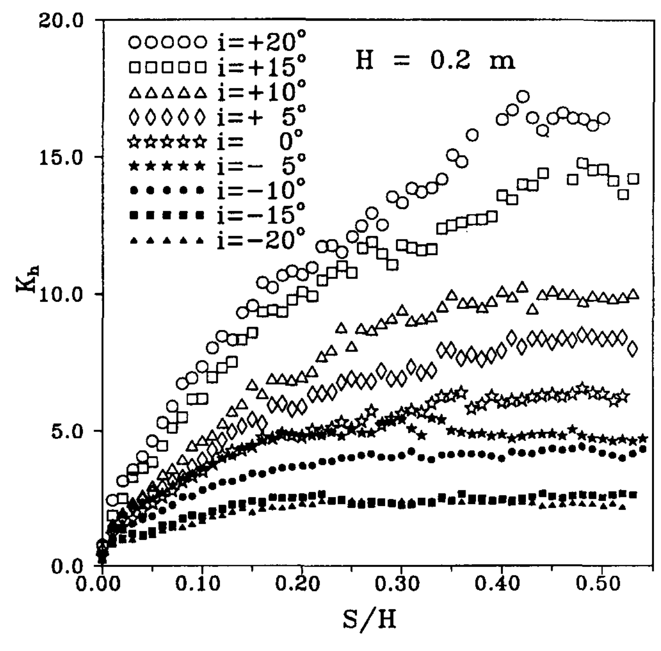

FIG. 15. Variation of K_h with Passive Wall Movement for Various Backfill Inclinations

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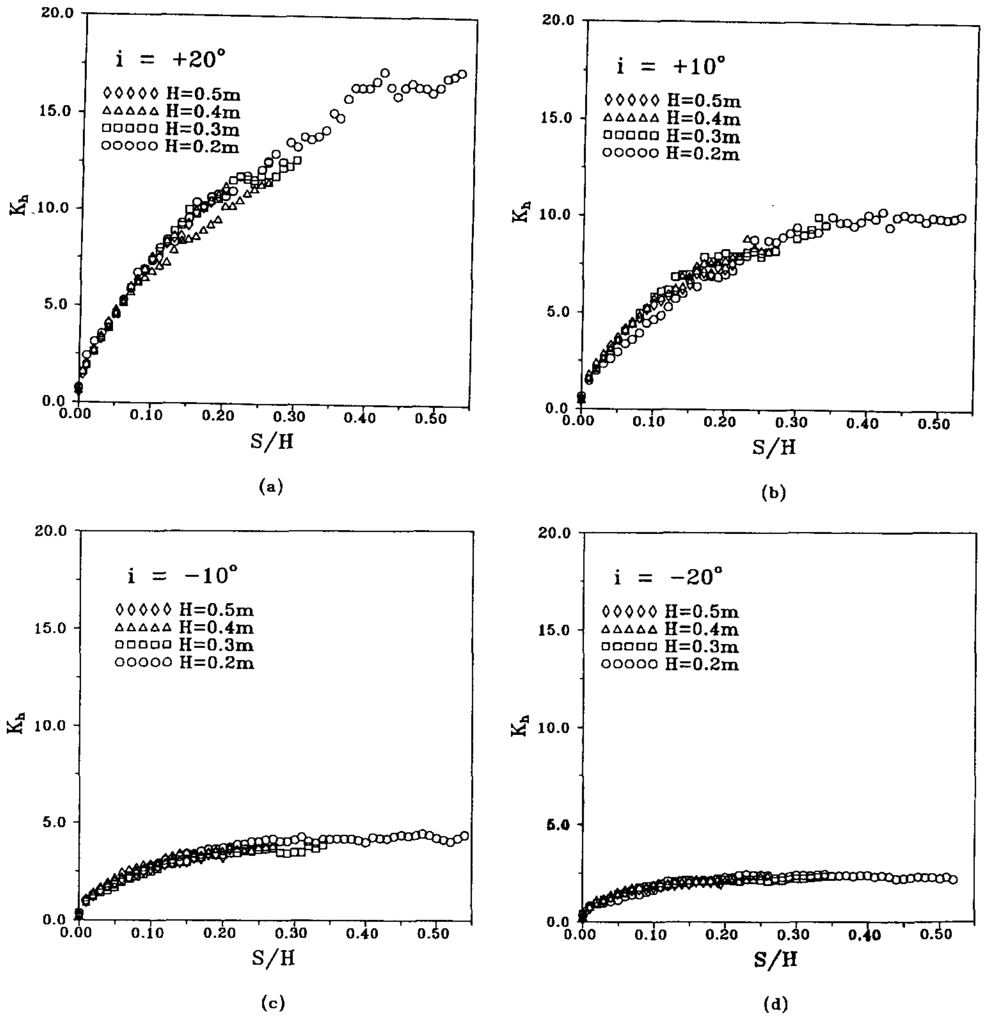

FIG. 16. Variation of K_h with Passive Wall Movement for Various i and H

Coulomb, Rankine, and Terzaghi's theories are also indicated in Fig. 14. It is obvious that the test data are in good agreement with the values determined with Coulomb and Terzaghi's theories. Rankine's solution tends to overestimate the active thrust, especially for the backfill with a negative sloping angle. The Rankine active earth-pressure coefficient K_a is given by the following relationship:

$$K_a = \cos i \frac{\cos i - \sqrt{\cos^2 i - \cos^2 \phi}}{\cos i + \sqrt{\cos^2 i - \cos^2 \phi}} \quad (1)$$

Referring to Fig. 2(a) and 2(c), whether the backfill inclination is $+20°$ or $-20°$, we will get the same K_a from (1). Since the Rankine active thrust P_a is always parallel to the surface of backfill, therefore for $i = +20°$ and $i = -20°$ the only difference is that the shearing components of P_a have opposite directions. However, for $i = +20°$ and $i = -20°$ the normal components of the Rankine active thrusts are exactly the same. Based on the experimental data shown in Fig. 14, it is obvious that it may not be appropriate to adopt Rankine's theory to determine the active earth pressure behind a rigid wall with sloping backfill.

PASSIVE TEST RESULTS

Wall with Sloping Backfill

The effect of backfill inclination on the development of passive stress are discussed. After the backfill has been placed into the soil bin, the model wall slowly moves toward the soil mass in translation mode at a constant speed of 0.27 mm/s. The variation of coefficient K_h for various backfill inclinations is summarized in Fig. 15. It is clear that K_h increases with wall movement before reaching an ultimate value; then K_h remains approximately a constant. This ultimate value is defined as the horizontal passive earth-pressure coefficient $K_{p,h}$. For the backfill with a negative sloping angle (e.g., $i = -20°$), a passive state is reached at a relatively small wall movement. On the other hand, larger wall movements are needed for the backfill with a positive sloping angle (e.g., $i = +20°$) to reach its passive state.

To study the effects of backfill height H on passive pressure, experiments with backfill heights of 0.2, 0.3, 0.4, and 0.5 m have been conducted. Figs. 16(a)–16(d) show the variation of K_h as a function of wall movement for various backfill heights for $i = +20°$, $+10°$, $-10°$, and $-20°$, respectively. It may be seen that most data are concentrated in a narrow band. It appears that, within the range tested, the backfill height has little influence on the development of passive stress. Due to the limitation of the experimental facility, the maximum wall movement allowed for the 120 mm thick model wall is only 110 mm. To ensure that a passive state would occur during testing, the $H = 0.2$ m condition is adopted in the following discussion. It should be mentioned that as the height of backfill H reduces from 0.5 to 0.2 m, the valid earth-pressure measurements on the retaining wall decreases from 10 to 4.

Figs. 17(a)–17(d) illustrate the distributions of earth pressures at various stages of wall movement for $i = +20°$, $+10°$, $-10°$, and $-20°$, respectively. From these data it may be seen that the experimental earth pressures are nearly linear at each stage of wall movement. This implies that the points of ap-

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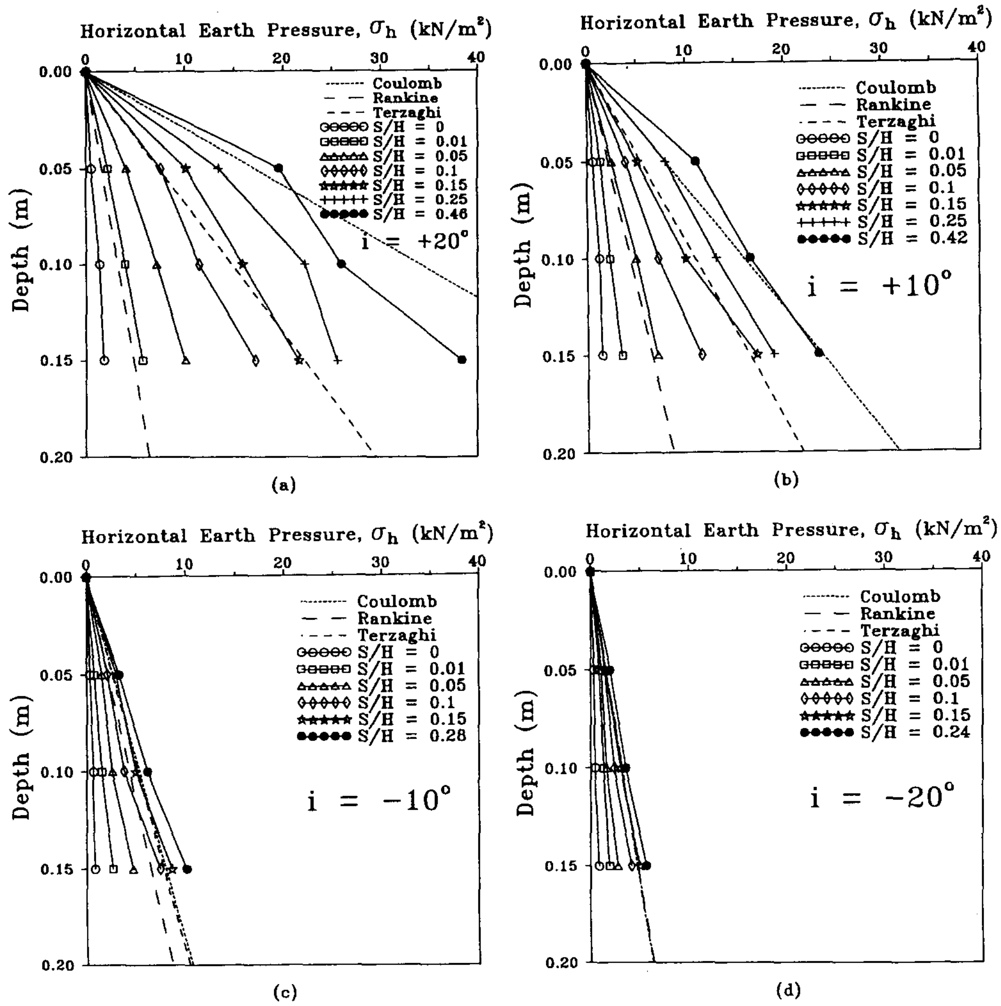

FIG. 17. Distributions of Horizontal Earth Pressure for Various Backfill Inclinations

plication of total thrust would act at about $H/3$ above the wall base. Passive earth-pressure distribution calculated with Coulomb, Rankine, and Terzaghi's theories are also indicated in Fig. 17. It should be stressed that, for $i = +20°$, the discrepancy among the theoretical solutions is quite significant. It may be observed in Fig. 17 that the experimental passive earth-pressure distributions are in relatively good agreement with Coulomb's solution for various backfill inclinations. Fig. 18 shows that, irrespective of the backfill sloping angle, the points of application of total thrusts varied between $0.33H$ and $0.41H$ above the wall base.

Fig. 13(b) shows that the wall movement required for the backfill to reach a passive state $(S/H)_p$ obviously increases with increasing backfill inclination. In the figure, for $i = +20°$, the passive wall movement needed is $0.46H$. The physical meaning of the preceding finding is that, for a retaining structure backfilled with 1.0 m of loose sand, the wall displacement required for the soil to reach a passive state would be as much as 0.46 m. From a practical point of view, even a portion of such a large lateral displacement could damage the function of the wall and nearby facilities. Under such a circumstance, when evaluating the adequacy of a retaining structure, except assessing the factors of safety associated with sliding, overturning, and bearing capacity, it might be necessary to establish a displacement criterion for the designers.

Based on his experimental results using a rotating model wall, Schofield (1961) reported that the wall movement required for a loose horizontal backfill to reach a passive state is approximately $0.2H$. However, the passive wall movement needed for a dense backfill would be much less (only

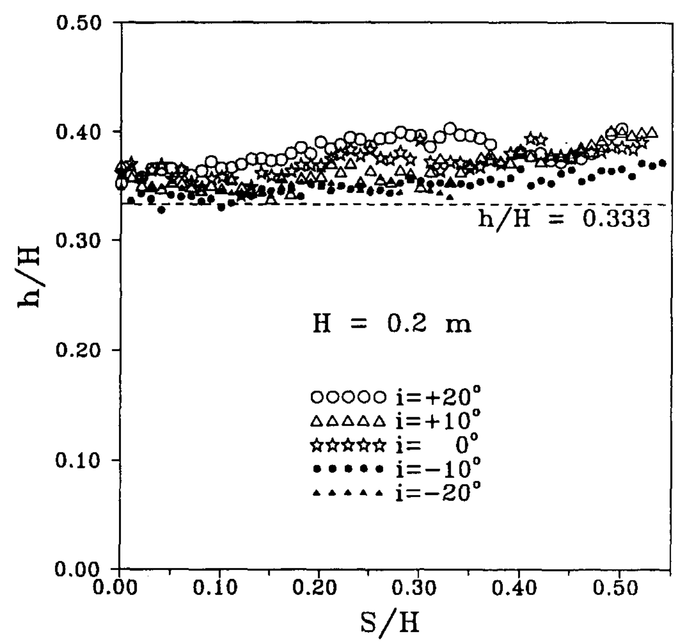

FIG. 18. Variation of *h/H* with Passive Wall Movement for Various Backfill Inclinations

$0.04H$). Similar findings were also reported by Mackey and Kirk (1967) and Narain et al. (1969). In this study, the soil density obtained was quite loose. The unusually high passive wall movement needed ($0.46H$) is most probably due to the

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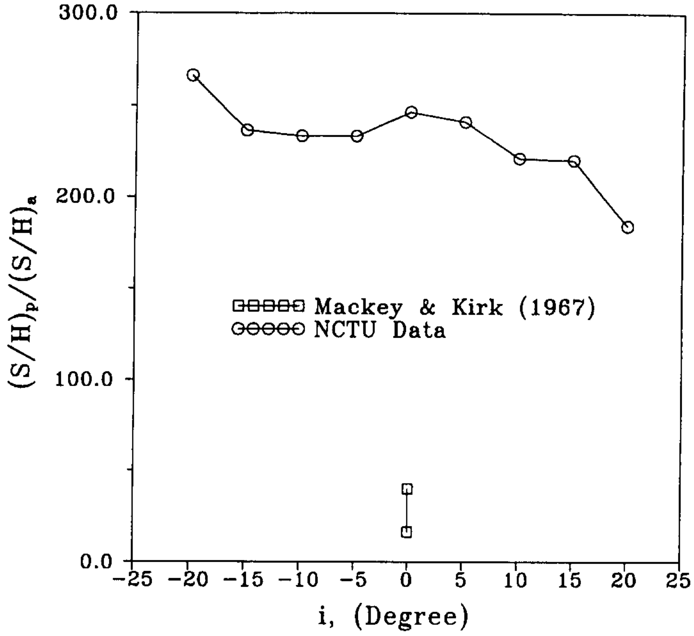

FIG. 19. $(S/H)_p/(S/H)_a$ versus Backfill Inclination

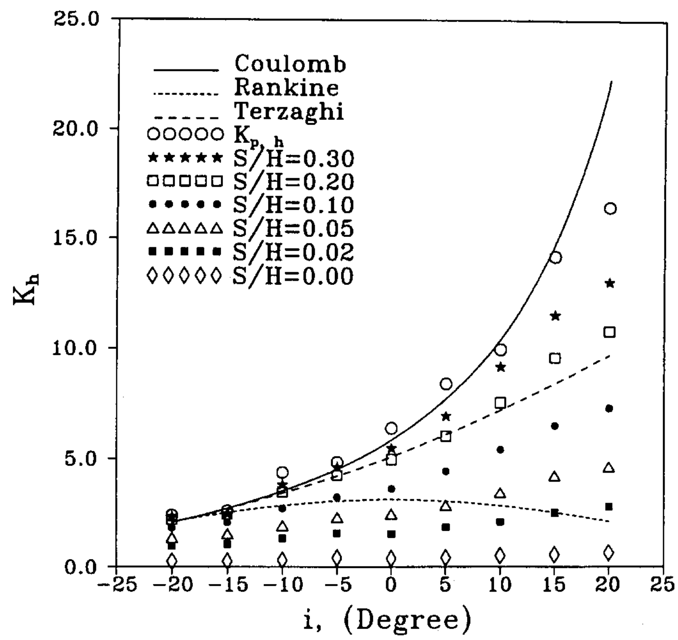

FIG. 20. Variation of K_h with i at Different Passive Wall Movements

combined effect of the soil density and the +20° backfill inclination.

The ratio of $(S/H)_p$ to $(S/H)_a$ as a function of backfill inclination is indicated in Fig. 19. On the average, the passive wall displacement required to reach a passive state is about 230 times the displacement required to reach an active state for the same wall. The low ratio reported by Mackey and Kirk (1967) is mainly due to the fact that their $(S/H)_a$ value is located at the high end of all data reported by different researchers shown in Fig. 13(a).

The relationship between the passive earth-pressure coefficient $K_{p,h}$ and backfill inclination is demonstrated in Fig. 20. It may be seen that $K_{p,h}$ increases with increasing sloping angle. It is clear that experimental $K_{p,h}$ values are in fairly good agreement with the results determined with the concept originally developed by Coulomb in 1776. Note that Rankine's theory tends to underestimate the passive thrust. The Rankine passive earth-pressure coefficient K_p is given by the following relationship:

$$K_p = \cos i \frac{\cos i + \sqrt{\cos^2 i - \cos^2\phi}}{\cos i - \sqrt{\cos^2 i - \cos^2\phi}} \quad (2)$$

Whether the backfill inclination is +20° or −20°, the K_p coefficient calculated with (2) would be the same. Although the shearing component of the passive thrust for i = +20° and −20° have opposite directions, however, the normal components of Rankine's passive thrust are identical. That is the reason why Rankine's K_h versus i relationship shown in Fig. 20 is symmetrical with the i = 0 vertical axis. In Fig. 20, the discrepancy between test data and Rankine's solution increases with increasing backfill sloping angle. For example, for i = +15° Rankines' passive thrust is only 18% of the experimental value. It should be mentioned that the $K_{p,h}$ values would occur at a large wall displacement as indicated in Fig. 13(b). For practical purposes the variation of K_h as a function of i angle at different stages of wall movement are also indicated in Fig. 20. It may be seen that, if S/H = 0.20 is arbitrarily assumed to be the displacement criterion for passive failure, then test data would be in fairly good agreement with the curve obtained with the log-spiral method proposed by Terzaghi.

CONCLUSIONS

Based on the experimental data obtained during the investigations, the following conclusions can be drawn about the effects of backfill inclination on the development of active and passive earth pressures.

For a wall moving away from the backfill, the experimental earth-pressure distributions are essentially linear at each stage of wall movement up to failure. The points of application of the total thrust are located at about 0.29H to 0.33H above the wall base for various backfill inclinations. An active state is reached at different depths nearly simultaneously. The wall movement required for the backfill to reach an active state increases with increasing backfill inclination. The experimental active earth-pressure coefficient $K_{a,h}$ is in good agreement with the values determined with Coulomb and Terzaghi's theories. Rankine's solution tends to overestimate the active thrust, especially for the backfill with a negative sloping angle. It may not be appropriate to adopt Rankine's theory to determine the active earth pressure against a rigid wall with sloping backfill.

For a wall moving toward the backfill, the experimental earth-pressure distributions are nearly linear at each state of wall movement. Irrespective of the backfill sloping angle, the points of application of total thrusts varied between 0.33H and 0.41H above the wall base. The experimental passive earth-pressure distributions are in relatively good agreement with that determined with the approach originally developed by Coulomb in 1776. The wall movement required for the backfill to reach a passive state increases with increasing backfill inclination. For the same wall the passive wall displacement required to reach a passive state is approximately 230 times the displacement required to reach an active state. Rankine's theory tends to underestimate the passive thrust. The discrepancy between test data and Rankine's solution increases with increasing backfill sloping angle. For a backfill inclination of +15°, the passive thrust calculated with Rankine's theory is only 18% of the experimental value. It may not be appropriate to adopt Rankine's theory to determine the passive earth pressure against the rigid wall with sloping backfill.

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APPENDIX II. NOTATION

The following symbols are used in this paper:

D_{10}, D_{60} = grain size for which 10 and 60% of soil by weight are finer;
e_{max}, e_{min} = maximum and minimum void ratios of soil;
G_s = specific gravity of soil;
H = height of backfill at soil-wall interface above wall base;
h = distance between point of application of total resultant force and wall base;
i = angle of backfill slope with horizontal;
K_a = active earth-pressure coefficient;
$K_{a,h}$ = coefficient of active horizontal soil thrust;
K_h = coefficient of horizontal soil thrust;
K_p = passive earth-pressure coefficient;
$K_{p,h}$ = coefficient of passive horizontal soil thrust;
P_a = resultant of active earth pressure;
P_p = resultant of passive earth pressure;
S = lateral wall displacement;
$(S/H)_a$ = wall movement required for backfill to reach active state;
$(S/H)_p$ = wall movement required for backfill to reach passive state;
z = depth measured from soil surface;
γ = unit weight of soil;
δ = friction angle at soil-wall interface;
σ_h = horizontal earth pressure; and
ϕ = internal friction angle of soil.

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